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(54) Boundary layer control device

(57) A boundary layer control mechanism primarily for aerofoil-type surfaces, in which one or more steps are formed in the surface. The step consists of a step recess followed, in the flow direction, by a ramp return to the surface contour. A number of such steps in succession on the suction surface of an aerofoil cause early, controlled separation of the boundary layer at each step, followed by re-attachment during each ramp. The boundary layer is thus continually 'nudged' into a condition which is resistant to gross separation. Applicable to turbine or compressor blades of turbo-machinery. Similar steps and ramps may be provided in the drum on which the blades are mounted.

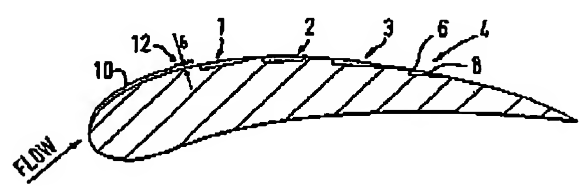

Fig .1.

The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

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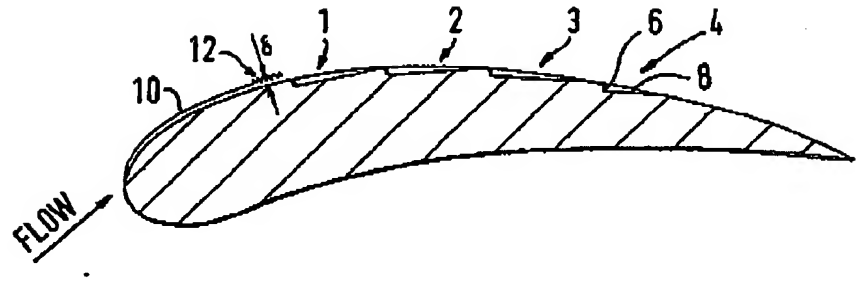

Fig .1.

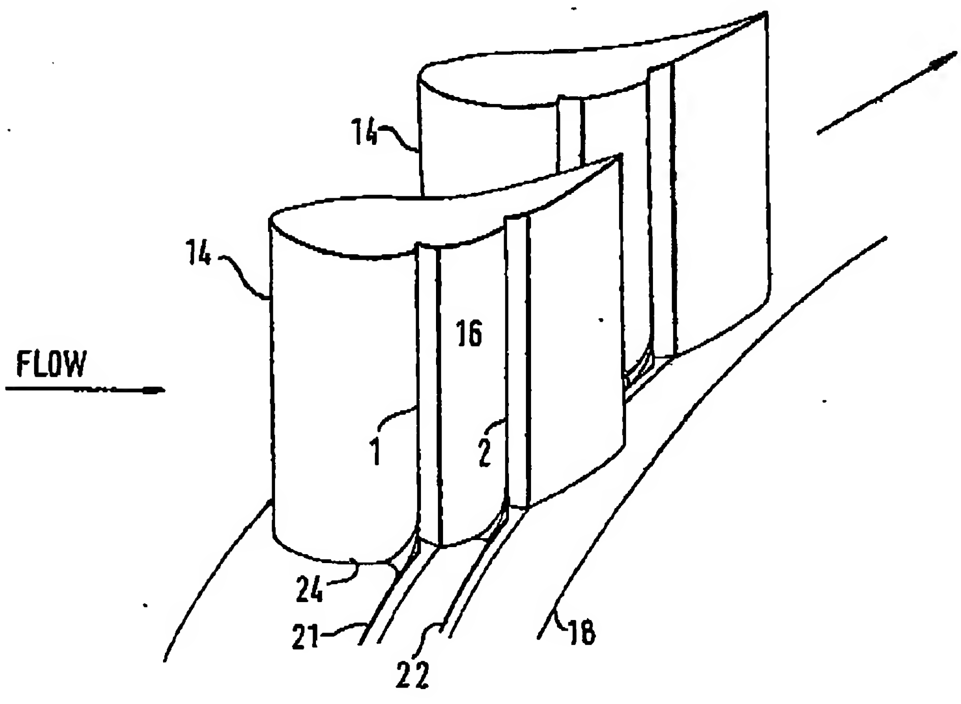

Fig .2.

SPECIFICATION

Boundary layer control mechanism

This invention relates to a hydro-dynamic mechanism for the control of boundary layer separation, particularly, but not exclusively in connection with aerofoil surfaces of turbo-machines such as the blades of turbines or compressors.

The loading of, for example, a turbo-compressor stage, i.e. the relative gain in pressure across the stage, is limited by the tendency of the boundary layer on the suction (i.e. convex) surface of the aerofoil blades to separate drastically towards the downstream end of the surface. The pressure across the suction surface (i.e. in the fluid flow direction) falls and then recovers to the higher output value, the recovery occurring over the trailing portion of the surface. It is this pressure recovery which causes or tends to cause the boundary layer to separate.

The effect of high pressure recovery, and thus of an excessive stage loading, is to produce gross boundary layer separation, turbulence at the trailing surface, energy losses and poor efficiency.

One object of the present invention is to provide a simple mechanism for controlling the boundary layer separation.

According to the present invention a hydro-dynamic mechanism for the control of boundary layer separation from a surface constraining fluid flow, the surface being subject, in operation, to pressure differences in the direction of the flow such as to tend to cause boundary layer separation, comprises the inclusion of a step extending transversely to the direction of flow and having a profile consisting of a stepwise recession of the surface followed in the flow direction by a ramp portion to the surface contour, the depth of the step and the length of the ramp portion being such as to cause separation of the boundary layer at the step and re-attachment within the ramp portion.

The step may be one of a plurality extending transversely to the direction of flow, the proximity of successive steps being such that after re-attachment separation by the next step occurs before the boundary layer returns to equilibrium conditions. The depth of step preferably approximates to the thickness of the boundary layer immediately prior to the step and the length of the ramp portion in the direction of flow is preferably not less than approximately ten times the depth of step.

Each step except the first may follow immediately on the preceding one.

According to another aspect of the invention, an aerofoil surface includes a hydro-dynamic boundary layer control mechanism as aforesaid, the step or steps being provided on the suction side of the aerofoil. In an aerofoil surface and including a plurality of steps, the first step in the flow direction preferably commences at the end of transition from a laminar to a turbulent boundary layer.

According to a further aspect of the invention, in a turbo-machine stator or rotor comprising an annulus and a multiplicity of aerofoil blades extending radially from the annulus, each blade has an aerofoil surface as aforesaid.

In such a case, the surface of the annulus from which the blades extend may be provided with a boundary layer control mechanism as aforesaid, the steps in the blades intersecting the steps in the annulus. At the inter-section of each blade step with an annulus step a metal fillet may be provided having an approximately triangular cross-section varying from zero size at an upstream point to a maximum size at the onset of the intersecting steps.

A boundary layer control mechanism in accordance with the invention will now be described, by way of example, with reference to the accompanying drawings, of which:

Figure 1 is a cross-section of an aerofoil blade incorporating the control mechanism, and

Figure 2 is a partly diagrammatic perspective view of part of a turbine rotor annulus incorporating the control mechanism.

If fluid flow over a surface is subjected to shock, a pressure rise occurs which is an extreme version of the pressure recovery that arises over the suction surface of an aerofoil blade. Separation of the boundary layer from the surface can then occur, leaving a region of recirculating fluid close to the surface. Velocity diffusion or dispersion across the region between the now separated boundary layer and the recirculating region occurs from the point of initial separation such that the velocity within the recirculating region is low and comparable to the previous boundary layer velocity close to the wall, while the velocity of the adjacent and higher streams of the boundary layer is greater and approaching the free flow velocity.

When the effects of the initial pressure gradient fade away, the boundary layer veers back towards the surface and re-attaches itself. The velocity profile, i.e. the velocity magnitude with distance from the surface, may now be seen to contain the majority of its variation over a distance very much less than previously. The profile has filled out as it were, to have a substantially flat front.

The resulting re-attached boundary layer is found to have a greater resistance to separation and an ability to retain this property for a distance of the order of ten times the boundary layer thickness from the point of re-attachment.

Referring now to Figure 1 of the drawings, this shows an aerofoil blade in cross-section. The convex, suction surface is formed with steps 1—4 which extend along the blade in parallel formation normal to the plane of the drawing. Each step comprises a sudden falling away of the surface, a stepwise recession 6, followed by a ramp portion 8 returning to the general surface contour. In this embodiment the steps follow one upon the other immediately.

Fluid flow over the suction surface produces a boundary layer 10 which starts to thicken and grow turbulent under the influence of the pressure

gradient along the surface at a point 12. The initial boundary layer has a velocity profile which increases smoothly from zero at the surface itself to the free flow velocity at the upper region of the boundary layer.

In the absence of the steps, the turbulent boundary layer would thicken progressively until gross separation occurred towards the tail end of the surface.

The effect of the first step is to produce a small degree of separation before it would otherwise occur, a small recirculation region being formed in the lee of the portion 6 of the step. There then occurs a velocity dispersion between the recirculation region and the separated boundary layer as described above, such that substantially the whole of the boundary layer acquires a near uniform velocity. Re-attachment of the boundary layer occurs within the ramp portion 8 of the step 1, the boundary layer tending to maintain its near uniform velocity distribution through this portion. This characteristic of the post-attachment boundary layer does, it is found, provide increased resistance to separation that could otherwise be caused by pressure recovery over the surface.

If only the one step is employed the re-attached boundary layer gradually reverts to the equilibrium condition in which the velocity profile changed smoothly and continuously throughout the thickness of the boundary layer. Protection or control of the boundary layer would therefore be provided for a short distance but following this the boundary layer would again be liable to gross separation with its attendant disadvantages of loss and inefficiency. This may, however, be a sufficient improvement in the uncontrolled arrangement.

Further improvement is, however, available in that the boundary layer may be maintained in a constant state of what might be called full-velocity-profile re-attachment by repeated controlled separations.

Thus at the end of the first step, when the boundary layer is about to 'forget' its acquired superior condition, a second controlled separation is imposed by step 2. Again the velocity dispersion occurs, followed by re-attachment as a full-velocity-profile boundary layer with its inherent resistance to pressure recovery separation.

The process is then repeated for a substantial part of the suction surface until permanent separation is either unavoidable or is unlikely to occur.

It may be seen therefore that by keeping the boundary layer in a continuous state of controlled and limited separation, uncontrolled gross separation can be avoided.

The dimensions of the steps are related to the flow conditions and particularly to the boundary layer thickness. The first step has a depth which is made approximately equal to the boundary layer thickness immediately before the step, i.e. δ at the point 12. Typical values of this thickness are in the range 0.7—2.5 mm. The 'memory' of the separation treatment imposed by the step persists after re-attachment for a distance of about ten times the boundary layer thickness so a minimum step length (i.e. of the ramp portion 8) of about 10δ leaves a margin of safety equal to the length of the separation region. Greater ramp portion lengths may be permissible in certain flow conditions.

The steps are not, ideally, of the same dimensions since the 'full-profile' boundary layer obtained after each re-attachment has a reduced displacement thickness, i.e. the boundary layer is effectively thinner. Thus the steps may become progressively shallower and shorter, depending upon the free stream conditions and particularly the pressure recovery rate. Measurements of the various boundary layer thicknesses in given conditions provide the necessary subsequent step dimensions.

The position of the first step is determined by the state of the boundary layer along the suction surface. A fairly definite transition occurs between the initial laminar boundary layer and the turbulent equilibrium conditions shown at the point 12. This transition can be detected by observation of any of a number of parameters. For example, the skin friction and heat transfer at the surface is found to rise sharply from a minimum to a maximum through this transition. Similarly the surface total pressure varies in the same way. The latter can be measured with a pitot tube, known as a Preston tube, mounted close to the surface.

The first step is then positioned at the end of this transition.

The aerofoil surface of Figure 1 may be the surface of a compressor rotor blade 14 as shown in Figure 2. In this drawing only two steps are shown for simplicity. All of the blades on the annulus are, of course, stepped in the same way.

Boundary layer control may also be employed on the annulus 18 on which the blades 14 are mounted. Steps 21 and 22 are provided in the annulus and these may be made to intersect the radial steps 1 and 2 of the blades.

The intersection of the blades 14 and the annulus 18 may be stepped in a 3-dimensional manner by employing a metal fillet on the immediate upstream side of each step junction, this fillet being of approximately triangular cross-section and of increasing size from zero at an upstream point 24 to a maximum in coincidence with the faces 6 of the steps 1/21 and 2/22.

While the blades 14 are shown as blades of a compressor rotor, they may equally be blades of a stator ring.

The steps in the aerofoil surface, while being transverse to the fluid flow, may be angled to the flow. They may also be of composite form such as, for example, the fishtail formation of a bird's feather.

It will be clear that the boundary layer control mechanism of the invention can find application in constructions other than turbo-machines. For example it can be used to control the boundary layer over vehicle body surfaces which are necessarily convex and subject to pressure

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recovery.

CLAIMS

1. A hydro-dynamic mechanism for the control of boundary layer separation from a surface constraining fluid flow, said surface being subject, in operation, to pressure differences in the direction of said flow such as to tend to cause boundary layer separation, said mechanism comprising the inclusion of a step extending transversely to the direction of flow and having a profile consisting of a stepwise recession of the surface followed in the flow direction by a ramp portion to the surface contour, the depth of the step and the length of the ramp portion being such as to cause separation of the boundary layer at the step and re-attachment within the ramp portion.

2. A boundary layer control mechanism according to Claim 1, wherein said step is one of a plurality extending transversely to the direction of flow, the proximity of successive steps being such that after re-attachment separation by the next step occurs before the boundary layer returns to equilibrium conditions.

3. A boundary layer control mechanism according to Claim 1 or Claim 2, wherein the depth of step approximates to the thickness of the boundary layer immediately prior to the step and the length of the ramp portion in the direction of flow is not less than approximately ten times the said depth of step.

4. A boundary layer control mechanism according to Claim 2 or Claim 3 as appendent to Claim 2, wherein each step except the first follows immediately on the preceding one.

5. An aerofoil surface including a hydro-dynamic boundary layer control mechanism according to any preceding claim, said step or steps being provided on the suction side of the aerofoil.

6. An aerofoil surface according to Claim 5 and including a plurality of steps, wherein the first step in the flow direction commences at the end of transition from a laminar to a turbulent boundary layer.

7. A turbo-machine stator or rotor comprising an annulus and a multiplicity of aerofoil blades extending radially from the annulus, each blade having an aerofoil surface according to Claim 5 or Claim 6.

8. A turbo-machine stator or rotor according to Claim 7, wherein the surface of said annulus from which said blades extend is provided with a boundary layer control mechanism in accordance with any of Claims 1—4, the steps in the blades intersecting the steps in the annulus.

9. A turbo-machine stator or rotor according to Claim 8, wherein at the intersection of each blade step with an annulus step a metal fillet is provided having an approximately triangular cross-section varying from zero size at an upstream point to a maximum size at the onset of the intersecting steps.

10. An aerofoil blade substantially as hereinbefore described with reference to Figure 1 of the accompanying drawings.

11. A compressor rotor annulus substantially as hereinbefore described with reference to Figure 2 of the accompanying drawings.

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